

Pulse-wise GRB correlation: implication as a cosmological tool

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Gamma-ray bursts (GRBs) are cosmological explosions which carry valuable information from the distant past of the expanding universe. One of the greatest discoveries in modern cosmology is the finding of the accelerated expansion of the universe using Type Ia supernovae (SN Ia) as standard candles. However, due to the interstellar extinction SN Ia can be seen only up to a redshift $z \sim 1.5$. GRBs are considered as the potential alternative to push this limit to as high as $z \sim 10$, a redshift regime corresponding to an epoch when the universe just started to form the first structures. There exist several correlations between the energy and an observable of a GRB which can be used to derive luminosity distance. In recent works, we have studied spectral evolution within the individual pulses and obtained such correlations within the pulses. Here we summarize our results of the pulse-wise GRB correlation study. It is worth mentioning that all GRB correlations are still empirical, and we cannot use them in cosmology unless we understand the basic physics of GRBs. To this end, we need to investigate the prompt emission spectrum which is so far generally described by the empirical Band function. We shall discuss our current understanding of the radiation process particularly the finding of two blackbodies and a powerlaw (the 2BBPL model) as the generic spectral model and its implication. This is a work in progress and we expect to obtain the most fundamental GRB correlation based on our improved spectral model.

Keywords: gamma-ray burst; observational; data analysis

1. Introduction

Gamma-ray bursts (GRB) are cosmological explosions which produce an enormous amount of energy $\sim 10^{50} - 10^{53}$ erg within a few seconds to a few minutes by means of a highly relativistic jet. A GRB light curve generally consists of a single or multiple broad pulses and rapid variability within the pulses on a timescale down to a few milliseconds.¹ On the other hand, the spectrum is a continuum which is generally attributed to an optically thin synchrotron emission.^{1,2} Interestingly, the spectrum generally shows a hard to soft evolution within the individual pulses.³ Hence, pulses are important and should be considered independently.

In recent works,^{4,5} we have given particular attention to the individual GRB pulses and obtained the timing and spectral informations. We have then used the GRB pulses to study GRB correlations^{6,7} similar to the Amati correlation⁸. Such studies are important due to several reasons: (1) As the correlation hold within the pulses it shows that the correlation is a pulse property, (2) it also shows that the correlation is real and not due to selection bias, (3) it provides a larger sample

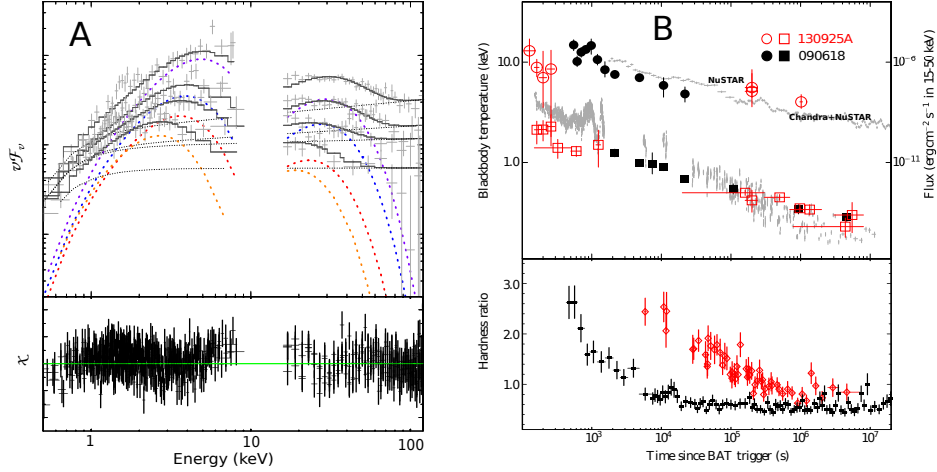


Fig. 2. (A) Time resolved BAT–XRT data of GRB 090618 fitted with the 2BBPL model (upper panel) and residual (lower panel). The two blackbodies are shown by dotted lines with different colors for different time bins. (B) Evolution of the temperature of the two blackbodies (upper panel) and the hardness ratio (lower panel) for two GRBs.^{18,19}

3. Radiation Mechanism — Thermal Component

The pulse model we have developed is an empirical one. It is worthwhile to mention that all GRB correlations are empirical and shows considerable data scatter. This is also found in our pulse-wise correlation study (Fig. 1A). Hence, it is important to understand the physical mechanism of pulse emission and spectral characteristics. In some studies, the synchrotron origin of the spectrum has been challenged by observations of a spectral photon index higher than -1.5 (or even higher than $-2/3$), which is disallowed in the fast cooling (slow cooling) regime.¹³

In recent works it is found that the GRB spectrum also contains a thermal component.¹⁴ In general the spectrum is a combination of the thermal and non thermal emission. However, the correct shape of the components is debatable, e.g., a blackbody+powerlaw (BBPL)¹⁴, multi-colour blackbody+powerlaw (mBBPL)¹⁵, two blackbodies+powerlaw (2BBPL)^{5,16–19}, 2BB+cutoff powerlaw (2BBCPL)¹⁸ etc. Moreover, the thermal emission is not always statistically significant. One way to find the correct model is to analyze the data with good spectral resolution e.g., *Swift* X-ray telescope (XRT), *NuSTAR*, *Chandra*. However, due to the focusing nature of these instruments such observations are rare. Recently, we have found two such cases, GRB 090618¹⁸ and GRB 130925A.¹⁹ In Fig. 2A, we have shown the 2BBPL model fitted to the time resolved data of GRB 090618 obtained from *Swift* burst alert telescope (BAT) and the XRT. In Fig. 2B the temperature and hardness evolution of this GRB is compared with that found for GRB 130925A observed with the XRT, the *NuSTAR* and the *Chandra*. We see a remarkable similarity of the spectral evolution which denotes a common radiation mechanism.

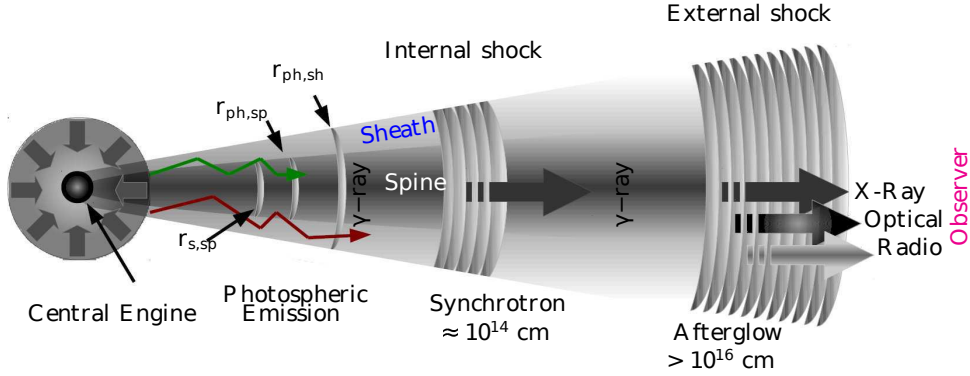


Fig. 3. A schematic of the spine-sheath jet¹⁸ (see text for detail).

We note here that the pulse emission in GRBs can have a wide variety. We have studied all such varieties and found a clear evidence of the two blackbodies in all cases, namely, (1) GRBs with single pulse⁵, (2) GRBs with separable multiple pulses¹⁶ and (3) those having highly variable lightcurve¹⁷. Hence, the model appears to be a generic spectral shape.

We suggest a spine-sheath jet structure to explain our observations (see Fig. 3).^{20,21} Such a structure is theoretically expected as the GRB jet pierces through the envelop of the progenitor star. The two blackbodies are produced at the two photospheres of the jet, while the photons crossing the boundary layer of the spine and sheath are inverse-Comptonized and form a cutoff powerlaw. In addition, internal shocks produced at larger radius will also contribute to the non-thermal emission. We are planning to pin down the mechanism by developing a spine-sheath jet model²² and then applying this model on a large set of GRBs to obtain the physical parameters of the jet.

4. Discussion

The 2BBPL model is primarily found to be consistent with the data in keV–MeV or lower (e.g., the XRT) energies. It is useful to apply this model to the prompt emission data in these energies and then investigate the predicted flux in other energies. In the following we perform such analysis to see how much we can explain the emission at very high energies (GeV) based on the spectral model fitted to the lower energy data.

The very high energy (GeV) emission is detected in some GRBs with *Fermi* large area telescope (LAT). This emission is delayed compared to the prompt keV–MeV emission by a few seconds. It is well known that the Band function cannot capture the wide spectrum from keV to GeV. Also, the GeV flux is found to be uncorrelated with the prompt keV–MeV flux. It is interesting to fit the keV–MeV data with the 2BBPL model and then compare with the flux at GeV energies. Analyzing a set

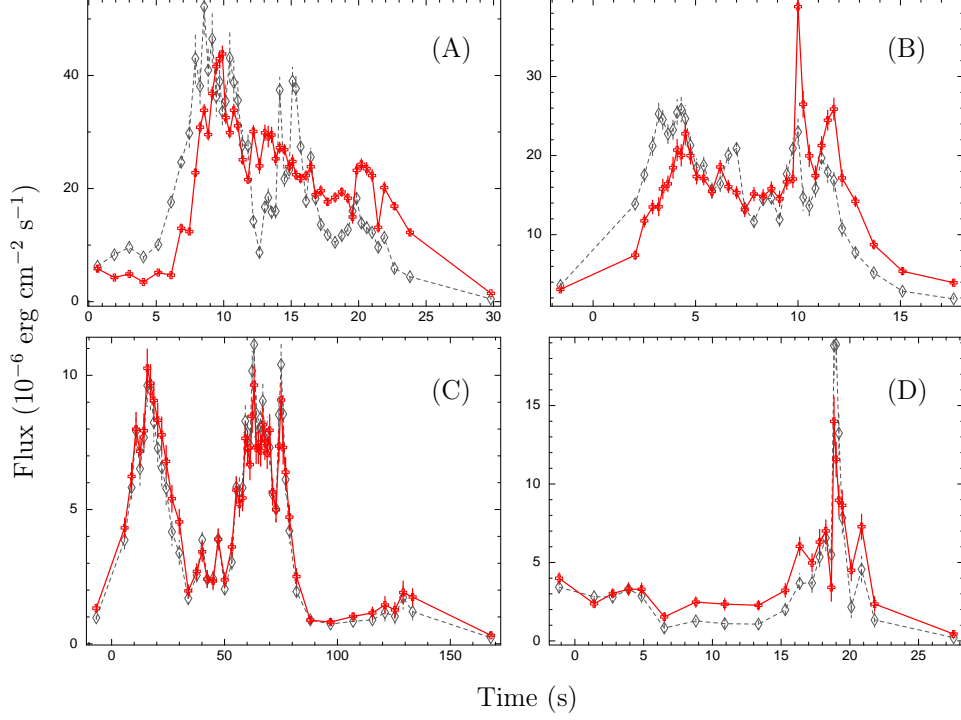


Fig. 4. Flux evolution of the total (black dashed lines) and the powerlaw (red solid lines) for GRBs with LAT detection.²³ GRBs with high LAT flux (A, B), and low LAT flux (C, D)

GRBs detected by the LAT, we find a significant correlation of the GeV photon fluence with that of the non-thermal (powerlaw) component of the 2BBPL model fitted to the keV–MeV data.²³ Also, the powerlaw flux of GRBs with high GeV emission tend to have a delayed onset, and this component lingers at the final phase of the prompt emission (see Fig. 4). Remembering that the GeV emission is delayed and long lasting than the keV–MeV emission, we strongly suggest that the powerlaw component of the 2BBPL model shares a common origin with the GeV emission. In the framework of the spine-sheath jet model, this emission is produced at higher radius probably by synchrotron emission. On the other hand, the GeV photons of GRBs with low GeV emission are probably produced due to inverse-Compton of photons crossing the spine-sheath boundary. Clearly such finding strongly validates the 2BBPL model.

In future we shall test whether one or more spectral components of the 2BBPL model can be used to study the GRB correlation. For example, in our pulse model we have assumed that the spectral evolution is given by the LK96 law. We have found that fitting the spectrum with an additional blackbody component leads to a similar evolution. Now, the blackbody temperature shows a similar behaviour as shown by the E_{peak} (see Fig. 5). Such findings give us hope to further improve the

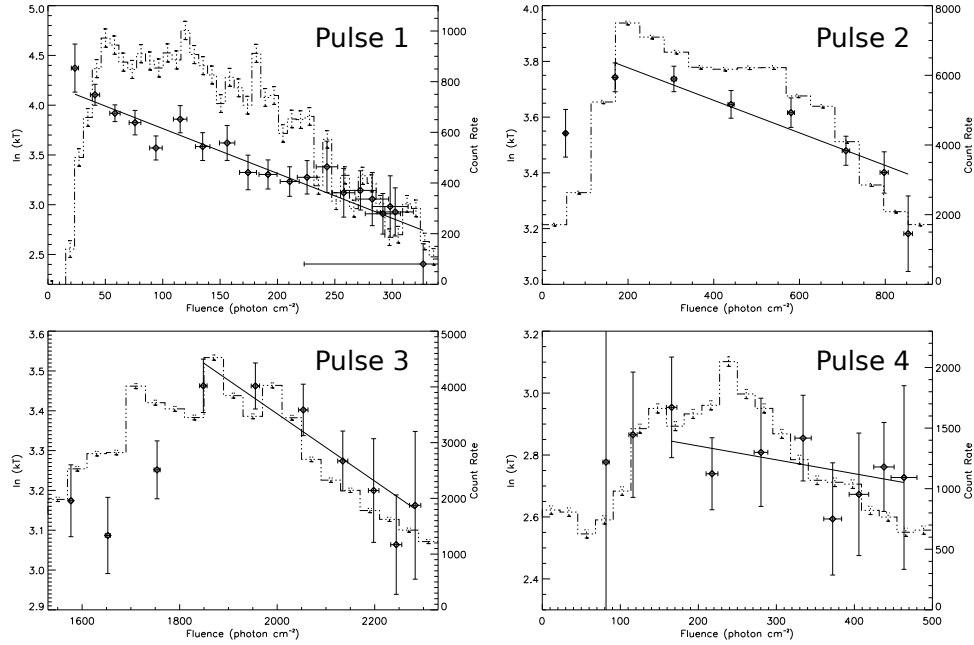


Fig. 5. Temperature evolution similar to the LK96 law¹¹ for the pulses of GRB 090618. The evolution is shown by the fitted solid lines while the count rates are shown by dot-dashed line.

pulse description and finally obtain the fundamental GRB correlation based on the physical spectral model.

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